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(54) **Contour extraction in multi-phase, multislice cardiac MRI studies by propagation of seed contours between images.**

(57) Contours are extracted from corresponding features, namely the left ventricular blood pool-endocardium interfaces, of a plurality of images collected as a multi-phase multi-slice cardiac Magnetic Resonance Imaging (MRI) study which are accessible by a computer in response to user input to the computer of a seed contour identifying the contour feature to be extracted in an initial image (I_{00})at a middle slice position and a predetermined phase position, namely end of diastole. From this as the only contour (CS) inputted by the user, contours are extracted from each image by a sequence of automatic propagation of determinations of extracted, or final contours by forming from a final contour (CF) for an image $I_{(00)}$, a seed contour for a not yet processed image ($I_{1,0}$,$I_{-1,0}$,$I_{0,1}$) which immediately adjoins in slice or phase position. For each image use is made of a seed-to-final propagation function in the form of an energy minimizing active contour function which has internal energy due to settable resistances to stretching and bending and image derived energy related to the gradient of the image. The final contour (CF) developed in the initial image (I_{00}) is passed as a provisional contour to images which immediately adjoin in phase position where they are further propagated by an in-phase provisional-to-seed propagation function and are passed to images which immediately adjoin in slice position, where they are further propagated by an in-slice provisional-to-seed propagation function. After extraction of the contours, and possible automatic post-processing for correction thereof, these contours are used by a computational or visualization application, such as the computation of an ejection fraction.

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BACKGROUND OF THE INVENTION

Field of The Invention

The present invention is generally directed to a method of extracting corresponding feature descriptive contours from a collection of images of slices of an object undergoing a repetitive motion cycle in response to an input of a seed contour proximate a feature contour in an image at given slice and motion cycle phase positions. In its more particular aspects, the present invention is directed to extracting such corresponding feature contours from magnetic resonance imaging (MRI) multi-image studies of the beating heart by automatic propagation of seed contours between images of different slices and/or between images of different phases.

Description of the Prior Art

MRI has become an invaluable medical diagnostic tool because of its ability to obtain high resolution in vivo images of a selected portion of the body, without invasion or use of ionizing radiation. In such imaging, a main magnetic field is applied longitudinally to an elongated generally cylindrical measurement space. The strength of this field determines the Larmor frequency of the relevant atomic nuclei (e.g. Hydrogen protons) to be excited. Sequences of radio frequency (rf) pulses, at or near this Larmor frequency, and magnetic field gradients are applied to the measurement space and resultant spin resonance signals, such as echo signals, are sampled. The collection of MR signal samples obtained from plural sequences applicable to the same slice are transformed in a processing unit, typically by Fourier transformation, to a two-dimensional array of pixel intensities which may be displayed on a display device or printed (typically to a film) as an image of the slice. It is common in MRI studies to make contemporaneous collections of MR signal data for plural images of the same body portion, such as parallel slices.

An interesting aspect of this imaging modality is that the image produced is not merely of the density of the relevant nuclei, but molecule type and/or motion dependent contrasts may be weighted as a function of the type and echo time of sequences utilized. For example, due to blood motion a spin-echo type sequence produces a "black blood" image because the relevant nuclei of the blood passing through the slice are not influenced by both excitation and echo rf pulses, while a small excitation angle fast gradient echo sequence produces a "white blood" image because the relevant nuclei of blood passing through the slice has not been depopulated of longitudinal magnetization spin states by prior excitation pulses.

The various configurations of the heart in its cycle of dilation and contraction are referred to as phases; these include the extremes of end of diastole and end of systole. Synchronizing information obtained from an electrocardiogram (ECG) is used either to trigger the evolution of the sequences for the desired phase(s) as in commonly owned U.S. Patent No. 4,903,704 or as a means for sorting of MR signal samples obtained in a free running fashion as in U.S. Patent No. 4,710,777. The image quality obtained varies dependent upon such conditions as echo time, phase position in the cardiac cycle and anatomic level of slice position, see P. Lanzer et al, "ECG-Synchronized Cardiac MR Imaging: Method and Evaluation", Radiology, Vol. 155, No. 2, June 1985, pp. 681-686.

Images for up to sixteen different phases are collectible with a currently available cardiac package of Philips Medical Systems (Release 4.7, February 1988). After data for plural images representing multiple slices and multiple phases thereof are collected and supplied to an imaging workstation, the phases for a slice may be there displayed sequentially as a movie. Such movies for different slices may be displayed in side-by-side fashion.

Contour feature extraction from the cardiac image may be used for computational purposes such as computing a measure of the volume of the blood pool in a ventricle when the extracted contour is the inner heart wall (endocardium). An ejection fraction may then be computed from such ventricular volume measures of the end of diastole and end of systole phase positions.

In the aforementioned currently available package, the user "draws" on the image displayed by the workstation an outline of the edges of the cardiac chamber or wall of interest, a so-called irregular region of interest (IROI) by means of an input device, such as a trackball, redrawing as necessary until the user is satisfied that the contour drawn sufficiently matches the image contour feature of interest. Furthermore, IROI's may be stored in a data base for potential use with differently weighted images of the same phase and slice. Alternatively, the workstation may use a roughly drawn contour input by the user as a guide to an edge detection procedure which searches for an edge-detected contour near the rough contour. The contour produced by edge detection may suffer from gaps, discontinuities in position or slope, multiplicities or other deficiencies which require editing or redrawing by the user. Furthermore, each different slice or

phase in which a contour is to be extracted requires the user to draw at least a rough contour therefor.

An energy minimizing active contour function termed a "snake" has been proposed in M. Kass et al, "Snakes: Active Contour Models", International Journal of Computer Vision (1988), pp. 321-331, as a means for locking on to local features such as edges, and contours in an image and once locked on, tracking them in motion or matching them in stereopsis. An energy functional is considered made up of the weighted sum of internal energy terms due to resistances to stretching and bending, image energy terms dependent on the type of feature the snake is to find, and external constraint energy terms, due to forces from such well behaved constructs as "springs" and point sources termed "volcanoes". The weighting of the resistances to stretching and bending indicate the degree to which the snake assumes a spatially smoothed contour. The "snake" active contour was further generalized in A. Amini et al, "Using Dynamic Programming for Minimizing the Energy of Active Contours in the Presence of Hard Constraints", Second International Conference on Computer Vision (Dec. 1988) pp. 95-99 to a dynamic programming in which the constraints imposed do not have to be spatially differentiable forces.

It is remarked that it is known from the article "Model guided automatic frame-to-frame segmentation in digital subtraction angiography" by J.H. Rong ***et al.***, in Proc. SPIE, Vol 1137, ***Science and Engineering of Medical Imaging*** (1989), pp. 31-36, to use a "snake" active contour model to determine the movement of points of the centerlines of blood vessels in digitally subtracted Röntgen images. Points of a centerline determined in one frame are projected onto a next image and used as an initialisation of the active contour model. There is no indication in that document to use the method for determining contours in a collection of images with a spatial relationship to each other.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide for contour extraction in multi-phase multi-slice image data, as from MRI cardiac studies, using an active contour model function in which the user need only draw a seed contour in one phase of one slice in order to extract corresponding contours from all phases and slices. It is a related object to provide a method for forming a seed contour for an image from the final contour generated for an adjoining phase or slice.

These objects are satisfied by choosing a first slice position which preferably corresponds to a "middle" slice, spatially, and a first phase position which, for MRI cardiac studies, preferably corresponds to the end of diastole, in phase. Then, with respect to an initial image at the first slice and phase positions, the user draws, by means of an input device, a seed (or rough) contour in the vicinity of the contour feature to be extracted. This seed contour is propagated to a final contour, fitting the desired true contour of the initial image, by means of a seed-to-final propagation function which comprises a series of iterations using a "snake" active contour model function utilizing an image energy term which is intensity gradient dependent. The resultant final contour for the initial image is propagated to the other images in the first phase position along an in-phase path directed from the initial image, in opposite directions successively by slice position. In this in-phase propagation between slices, the final contour of the initial image is a provisional contour for the two in-phase images of the slices immediately preceding and immediately succeeding the first image in slice position.

These provisional contours are propagated to seed contours for these two in-phase images by means of an in-phase provisional-to-seed propagation function. Then, as with the first image, the resultant seed contours are propagated to final contours for the two images by the seed-to-final propagation function. Such propagation continues to the other images in the first phase position, successively, by alternate application of the in-phase provisional-to-seed and the seed-to-final propagation functions, until final contours are generated in each image in the first phase position.

The final contours generated in the plurality of images in the first phase position (including the initial image) are further propagated in respective in-slice paths directed from the respective images in the first phase position, in opposite directions by phase position. In each in-slice path there is repeated alternate application of an in-slice provisional-to-seed propagation function and the seed-to-final propagation function until final contours have been generated in each image.

A further feature of the invention is that the in-phase provisional-to-seed propagation function comprises application of a correspondence matching procedure followed by application of a smoothing procedure using a limited number of iterations of the "snake" active contour function in the absence of image or constraint energy terms, while the in-slice provisional-to-seed propagation function comprises two sequential applications of the "snake" active contour function, both with internal energy parameters set to stiffen the "snake". The first application of the "snake" active contour function is in the presence of an image gradient term and, where needed, an image derived constraint term in the form of repelling bands, termed a barrier,

including an operative portion proximate the outer heart wall (epicardium). In the second application of the "snake" active contour function, an image derived constraint term in the form of an attractive band, termed a "Canny edges", including an operative portion proximate the inner heart wall (endocardium).

Another feature of the invention is that, in order to simplify computation, the same barrier is used for all phases of any slice which because of apparent relative thinness of the heart wall, requires a barrier. Such a barrier is also used in application of the contour function for seed-to-final contour propagation.

BRIEF DESCRIPTION OF THE DRAWING

Other objects, features and advantages of the invention will become apparent upon perusal of the following detailed description of the preferred embodiment when taken in conjunction with the appended drawing, wherein:

Figure 1 is a pictorial representation of a multi-slice multi-phase collection of images illustrating the paths of contour propagation;

Figure 2 is a flowchart overview of the contour extraction method of the present invention, including blocks which perform the contour propagations in the paths of Figure 1;

Figure 3A is a block representation of an adaptable active contour function;

Figure 3B is a block representation of the active contour function of Figure 3A adapted to propagate a seed contour to a final contour, detailing a block in Figure 2;

Figure 4 is a flowchart of a barrier calculation, detailing another block in Figure 2;

Figure 5 is a flowchart detailing yet another block in Figure 2, namely an in-phase propagation of a final contour in a previous image to a seed contour in a current image which is of an adjoining slice;

Figures 6A and 6B are pictorial representations of related portions respectively of previous and current images, which representations are used to illustrate the procedure employed in a correspondence match function block in Figure 5;

Figure 6C is a flowchart detailing the correspondence match function block of Figure 5;

Figure 7 is a flowchart detailing still another block in Figure 2, namely an in-slice propagation of a final contour in a previous image to a seed contour in a current image which is of an adjoining phase;

Figures 8A and 8B are pictorial representations of respectively correctly and incorrectly determined final contours for illustrating the underlying procedure employed in a post-processing block in Figure 2; and

Figure 8C is a flowchart detailing the post processing block in Figure 2.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The method of the present invention is directed in general to extracting a contour feature in a collection of images of slices of an object undergoing a repetitive motion cycle, by the steps of using an extracted contour for an image at a given slice position and given phase position in the motion cycle for automatically determining seed contours for an image at an adjoining slice or phase, which seed contour is used to automatically determine an extracted contour. The repeated application of these steps according to a propagation sequence allows for the determination of extracted contours from all images in the collection based on providing a user-input seed contour for only one of the images. This method is particularly useful for extracting a contour feature such as an inner wall of a ventricle from multi-slice multi-phase MRI data.

Referring first to Figure 1 of the drawing, there is illustrated such a multi-slice multi-phase cardiac MRI study comprised by a collection of bins of image data, **I**, each bin containing data for a rectangular grid of pixels for an associated image at a different combination of slice position and phase position in the beating cycle. Each bin of image data is accessible to data processing apparatus, preferably of the workstation type (not shown), and the associated image displaceable on a display portion thereof. For purpose of illustration of the sequence of propagation of determinations by the data processing apparatus of extracted contours, the bins are shown arranged in a two dimensional array to indicate by the bin's vertical and horizontal locations in the array, the position of the associated image, **I**, respectively, as to slice and phase. More specifically, the image data bins are ordered vertically in a series of consecutive parallel positions of slices from basal to apical and horizontally in consecutive phase positions, beginning through ending the diastolic phase and the systolic phase. A typical collection may comprise six slice positions and ten phase positions.

In accordance with the present invention, an initial one of the images $\mathbf{I}_{0,0}$ corresponding to an image data bin at a predetermined slice and phase position is displayed and the desired contour feature is identified by the user "drawing" a seed contour **CS** along the desired contour by input to the data processing apparatus via a suitable curve input device such as a trackball, mouse, light pen, digitizing tablet, or "touch" sensitive display overlay. The predetermined initial slice position is preferably a "middle"

slice in the series, for substantially symmetric propagation between slices. Where the number of slice positions is even, "middle" includes either of the two slices on opposite sides of the middle of the series. Further, the initial phase position is preferably the end of diastole because such images have been found to have less artifacts. As shown further in Figure 1, the path of determinations of extracted or final contours **CF** proceeds in opposite directions (vertically) from the initial image, slice by slice in the initial phase position, and in opposite directions (horizontally) from each slice in the initial phase position, phase by phase in the same slice position. In each current image after the initial image, the final contour propagated from a previous image to a current image is first propagated to a seed contour for the current image, which seed contour is used in the same manner as in the initial image to produce a final contour for the current image.

With this background, the overview of the inventive method indicated by Figure 2, supplemented with Table 1, will now be discussed. In the initial step indicated by block **10**, the multi-slice multi-phase MRI data collected by MRI scanning of a patient, is input to a memory or mass storage device (not shown) accessible to the computer. Then, in block **12**, the bins of image data are ordered as to slice and phase position, which sets up the propagation sequence indicated in Figure 1. Next, it is determined in block **14** whether based on the nature of the MRI study (barriers are needed for gradient-echo but not spin-echo studies) any barriers are needed in slice positions where the heart wall has at least a portion of apparent reduced thickness, as is typical in apical slices. As will become clearer as the discussion proceeds, a barrier is a collection of bands of image energy along edges of a thresholded image, which energy is opposite in sign to the energy due to the gradient of the image at the contour feature to be extracted. An operative band of the barrier is to be positioned proximate the heart wall opposite the contour feature to be extracted in order to repel an active contour away from the opposite wall. In the exemplary case where the desired contour feature is the inner wall of a heart chamber, such as a ventricle, in order to define the outer boundary of the blood pool in the ventricle, the barrier is to be positioned substantially along the outer wall of the ventricle. Preferably, the data processing apparatus automatically schedules a barrier calculation **16** for each slice, when the MRI image data was produced by a gradient echo sequence, in view of artifacts common in such a sequence.

Thereafter, in block **18**, as heretofore described, a seed contour **CS** is input by the user proximate the contour feature to be extracted in the initial image. This seed contour **CS** is in block **20** propagated to a final contour **CF** utilizing a "snake" active contour model as the seed-to-final propagation function. This active contour model and its application to seed-to-final propagation will be further discussed in conjunction with Figures 3A and 3B.

The final contour **CF** resulting from this processing of the initial image $\mathbf{I}_{0,0}$ (Figure 1) is passed to a first pair of images $\mathbf{I}_{1,0}$ and $\mathbf{I}_{-1,0}$ at the initial phase position which respectively immediately succeed and immediately preceded the initial image in slice position. This is accomplished as a result of identifying in block **22** unprocessed images at the initial phase position which immediately adjoin an already processed image in slice position, and consequently taking a "yes" output branch from block **22**. The passed final contour, is considered a provisional contour **CF'** in each of the first pair of images. Provisional contour **CF'**, is for each image of this pair propagated by block **24** to a seed contour. Block 24 performs an in-phase provisional-to-seed propagation function which will be more fully detailed in conjunction with discussion of Figures 5 and 6A-6C. The seed contours **CS** developed in block **24** are propagated in block **20** to final contours **CF** for the first pair of images $\mathbf{I}_{1,0}$ and $\mathbf{I}_{-1,0}$. These final contours **CF** are passed, as a result of again taking the "yes" output branch of block **22**, to image $\mathbf{I}_{2,0}$, immediately succeeding image $\mathbf{I}_{1,0}$ 0 and to image $\mathbf{I}_{-2,0}$, immediately preceding image $\mathbf{I}_{-1,0}$ in slice position. In the same manner, propagation continues through the loop comprising blocks **20**, **22** ("yes" output branch) and **24** until the entire sequence of determinations of the final contours **CF** in each of the images in the initial phase position has been accomplished. When the last pair of images, $\mathbf{I}_{K,0}$ and $\mathbf{I}_{-K,0}$ have been processed, the "no" output branch of block **22** is taken to block **26**.

In block **26**, unprocessed images are identified which adjoin a processed image in phase position. Each identification of such an adjoining unprocessed image results in taking a "yes" output branch from block **26** and the passing of the final contour **CF** from the processed image to the adjoining unprocessed image where it is considered a provisional contour **CF'**. This provisional contour **CF'** is propagated to a seed contour **CS** in block **28** by an in-slice provisional-to-seed propagation function which will be further detailed in conjunction with the discussion of Figure 7. The seed contour **CS** output from block **28** is propagated to a final contour **CF** for the previously unprocessed image. As should now be apparent, a loop comprising blocks 20, 22 ("no" output branch), 26 ("yes" output branch) and 28 produce a separate path of in-slice propagation of determinations of final contours **CF** in opposite phase directions from each image in the initial phase position. For example, the in-slice propagation from the initial image $\mathbf{I}_{0,0}$ begins with identification in block **26** of a third pair of images $\mathbf{I}_{0,1}$ and $\mathbf{I}_{0,-1}$ immediately succeeding and immediately preceding the initial image in phase position. As a consequence, the final contour **CF** from initial image $\mathbf{I}_{0,0}$ (in addition

to being passed to the first pair of images $I_{1,0}$ and $I_{-1,0}$ for in-phase propagation) is passed to third pair of images $I_{0,1}$ and $I_{0,-1}$ as a provisional contour **CF'** which is propagated in block **28** individually for each of images $I_{0,1}$ and $I_{0,-1}$ to respective seed contours **CS**.

When all images have been processed, the "no" output branch of block **26** is taken to block **30**, for the purpose of performing any necessary correction of a final contour **CF**, as will be further discussed in conjunction with Figure 8, in order to produce a set of extracted contours **CE**. Such correction is considered only when the MRI data is from a gradient-echo study. Lastly, the extracted contours **CE** are utilized in applications block **32**. A typical application is the calculation of the volume of the space enclosed by a surface at a particular phase, such as the blood pool enclosed by the endocardium of the left ventricle at diastole (maximum expansion) and systole (maximum contraction). This volume is calculated according to well known numerical methods utilizing a set of sample points along the extracted contours corresponding to the surface at the particular phase and a priori knowledge of the spacing between slices. The difference between the volumes of the blood pool at diastole and systole divided by the volume thereof at diastole gives the ejection fraction. While only the extracted contours for these two phases are needed for computation of ejection fraction, the availability of extracted contours for all phases enables a dynamical graphical three-dimensional perspective rendering of heart surfaces and walls.

A generalized active contour function **ACF** in the nature of the energy minimizing "snake" proposed by M. Kass et al will now be described for propagating an input contour $\mathbf{C_{IN}}$ to an output contour $\mathbf{C_{OUT}}$. Figure 3A illustrates that the generalized active contour function **ACF** is made adaptive by the values of various parameters and presence or absence of various image and constraint terms being settable. This allows use of function **ACF** in implementing contour propagation blocks **20**, **24**, and **28**.

Some theoretical background from M. Kass et al is useful in understanding the operation of active contour function **ACF**. An energy functional E* for the contour is, in general:

$$E^* = \int_c E_{INT}(v(s))\,ds + \int_c E_{IMAGE}(v(s))\,ds + \int_c E_{CON}(v(s))\,ds$$

where:

v(s) is a vector to points x(s), y(s) on the contour,

E_{INT} is internal energy,

E_{IMAGE} is image energy, and

E_{CON} is constraint energy.

The internal energy E_{INT} due to stretching and bending of the contour is taken as:

$$E_{INT} = (\alpha(s)\,|\,v_s(s)\,|^2 + \beta(s)\,|\,v_{ss}(s)\,|^2)/2$$

where:

$\alpha(s)$ and $\beta(s)$ are respectively resistances to stretching and to bending, generalized to vary along the contour, and

v_s and v_{ss} are respectively the first and second spatial derivatives of the contour.

In order to define a suitable image energy function which has local minima at edges, E_{IMAGE} is chosen as the negative of the square of the intensity gradient, as follows:

$$E_{IMAGE} = -\,|\,\Delta M(v(s))\,|^2$$

where:

M(v(s)) is the intensity of the image at points along the contour, and

Δ is the gradient operator $\partial/\partial x\,\hat{a}_x + \partial/\partial y\,\hat{a}_y$.

Terms making up the constraint energy E_{CON} may take a variety of forms depending on the contour extraction problem posed. In the exemplary typical situation where the contour feature to be extracted is the inner wall of the ventricle, the constraints used may include a so-called "barrier" having an energy term **IB** in the form of a band of positive energy lying approximately along the outer heart wall to repel the contour and a so-called "Canny edge" having an energy term **IC** in the form of a band of negative energy lying approximately along the inner heart wall to attract the contour away from the outer heart wall. An additional constraint comprises one or more so-called "volcanos" in the form of respective point sources, each having a positive energy function **V** in proportion to the inverse of the distance from the point source. The latter may be clipped or otherwise limited very close to the point source. Volcanos may be placed outside the outer heart wall to repel the contour.

The above relationships may be discretized spatially by sampling the closed contour so that it is

divided into N consecutive points (such as i=0 to 63) spaced apart by N-1 equal distances along the contour and dynamic parameters such as viscous friction may be added for the purpose of stabilizing the temporal evolution of the output contour in successive time steps each corresponding to an iteration number. The iterative equations can then be written in matrix form as follows:

$$x_n = (A + \Gamma I)^{-1}(x_{n-1} - f_x(x_{n-1}, Y_{n-1}))$$
$$y_n = (A + \Gamma I)^{-1}(y_{n-1} - f_y(x_{n-1}, y_{n-1}))$$

where:

x_n and y_n are column vectors of the set of consecutive points along the contour as a result of the nth iteration,

x_{n-1} and y_{n-1} are column vectors of the set of consecutive points along the contour as a result of the (n-1)th iteration,

A is a pentadiagonal banded matrix (plus three elements in upper right and lower left corners) containing terms which are arithmetic combinations of the coefficients α_i and β_i at the various points along the contour,

I is the identity matrix,

Γ is the friction coefficient,

f_x and f_y are spatial partial derivatives of $E_{IMAGE} + E_{CON}$ respectively with respect to x and y.

Such iterations may continue until a convergence is declared as a result of fluctuation of the energy function E* being small in successive iterations, or upon reaching a predetermined maximum number of iterations **MI**.

In the present invention, for the types of contours to be extracted from cardiac **MRI** studies, making α and β constant over the contour yielded satisfactory results and simplifies the content of the matrix A. It is recognized however that in general the ability to assign different α and β at special portions of the contour, such as those of extreme curvature, may be beneficial.

The generalized active contour function **ACF** will now be readily understood with reference to Figure 3A. Therein, the values of parameters α and β (where constant, or a scaling factor where not) and MI are passed to active contour function ACF as well as indications of whether the energy functional is to include the image energy term E_{IMAGE} and any of three possible terms making up constraint energy E_{CON}. The image energy term is referred to as **IG** (for image gradient) and the three possible terms making up the constraint energy are **IC** (for image "Canny edge"), **IB** (for image barrier) and **V** (for volcano). Thus, setting the stiffness of the active contour (α, β), the maximum number of iterations **MI** and the presence or absence of energy terms **IG**, **IC**, **IB**, and **V** make the active contour function ACF adaptable to various different contour processing tasks.

In Figure 3B, block 20 for propagating a seed contour **CS** to a final contour **CF** is shown as comprising a first active contour function **ACF1** with α = 1, β = 1, MI =150 in the presence of image gradient **IG** and of barrier **IB** terms, the latter being only for predetermined slice(s), generally the one or two most apical slices of gradient echo cardiac MRI studies, where the heart wall appears reduced in thickness and artifacts may be present.

The determination of barrier energy bands for the image barrier term IB will now be discussed in conjunction with Figure 4 and Table 2. It has been found that the motion of the outer heart wall of the left ventricle is sufficiently limited that the same barrier contour may be used in each phase position of the predetermined slice. Thus, the corresponding pixels of all images of the predetermined slice are averaged in block **34** to form an average image. The mean intensity μ and the standard deviation σ of the intensity are computed respectively in boxes **36** and **38** and a threshold intensity T is formed in block **40** as $\mu - \sigma/4$. The averaged image is then threshold in block **42** at threshold T to form a binary image, i.e. white where the intensity of the average image is greater than or equal to threshold T and elsewhere black. This binary image is processed by the "Canny Function" edge detection function block **44** to extract the boundaries of the binary image.

Function block **44** detects these boundaries using a "feature synthesis" edge marking technique of J. Canny, "A Computational Approach to Edge Detection", IEEE Transactions on Pattern Analysis and Machine Intelligence, VOL. PAMI-8, No. 6, November 1986, pp. 679-698. Essentially, edges are marked according to thresholding with hysteresis, the results of convolving the thresholded image with an edge responsive filter operator or kernel such as the derivative of a Gaussian. The use of hysteris implies two different thresholds are used for marking a group of connected pixel positions such that the operator output when centered about at least one of the pixel positions of the group exceeds a higher threshold and exceeds a lower threshold when centered about each pixel position of the group. Thus connected pixels tend to be marked, and thereby extracted as the barrier.

In-phase provisional-to-seed propagation function block 24 is detailed in Figure 5 as comprising a correspondence match function block **46** which produces a so-called noisy contour **CN** which is applied to a second active contour function block **ACF2** that spatially smooths contour **CN**. This spatial smoothing is accomplished by using a normal stiffness (α = 1, β = 1), a limited number of iterations (MI = 20), and turning off all image and constraint terms.

Correspondence match function block **46** will be understood by first referring to Figures 6A and 6B respectively representing corresponding portions of previous and current images $\mathbf{I}_p$ and $\mathbf{I}_c$. At each sample point ion the final contour **CF** in previous image I_p there is identified a line of uniformly spaced consecutive sample points interpolated from the grid of pixels, termed a profile $\mathbf{PR}_{pi}$, which line is centered about point i and extends normal to contour **CF** equally in opposite directions. The number of sample points in each profile PR_{pi} is a first predetermined number, e.g. 11-17. In the current image I_c where the final contour **CF** of previous image I_p is considered a provisional contour **CF'**, a profile $PR_{c,i}$ is identified at each point i along contour **CF'**. Each profile $PR_{c,i}$ also comprises a line of sample points normal to contour **CF'** and extending equally in opposite directions from point i. However the number of sample points in each profile $PR_{c,i}$ is a second predetermined number about two to three times the first predetermined number, e.g. 25-35. Now with reference to Figure 6C, and Table 3, each pair of corresponding profiles ($PR_{p,i}$;$PR_{c,j}$) is considered separately. In block **48** the profile $PR_{p,i}$ is displaced along profile $PR_{c,i}$ and for each displacement a correlation coefficient and a mean squared error between the intensities of registered sample points of the profiles are computed in blocks **50** and **52**. In subtraction step **54**, the mean squared error is subtracted from the correlation coefficient to form a match measure. Block **56** returns the displacement for which the match measure between the profile pair ($PR_{p,i}$;$PR_{c,i}$) is maximum. A point on profile $PR_{c,i}$ at that displacement from point i is taken as a point on noisy contour **CN**.

Figure 7 details the in-slice provisional-to-seed propagation function block **28**. Therein, the provisional contour **CF'** is applied to a third active contour function block **ACF3** where the stiffness is set to ten times normal (α = 10, β = 10), a normal number of iterations is used (MI = **150**) and image gradient **IG** and image barrier **IB** (for apical slice(s) of a gradient-echo study) terms are turned on. The large α causes the provisional contour **CF'** to reduce or shrink in size to a reduced contour **CR** which is substantially entirely in the blood pool. Reduced contour **CR** is applied to block **58** where the mean μ and standard deviation σ of the intensities of the pixels within reduced contour **CR** are determined. These quantities are applied to block **60** where a threshold $T = \mu - 1.5\,\sigma$ is formed and the current image $\mathbf{I}_c$ is thresholded in block **62**, using that threshold T, to a binary image which is applied to "Canny Function" block **64** which is of the same form as block **44** in Figure 4. The manner of computation of threshold T substantially assures that the output of "Canny Function" block **64** is the "Canny edge" energy function IC including an operative energy band at the blood pool inner heart wall interface.

Reduced contour **CR** is applied to a fourth active contour function block **ACF4** in which the active contour remains at ten times normal stiffness (α = 10, β = 10), at a normal maximum number of iterations (MI = 150) but with only the "Canny edge" constraint energy term **IC** turned on. Thus the fourth active contour function block **ACF4** utilizes the "Canny edge" term **IC** developed by function block **64**.

Reference is made to Figures 8A and 8B with respect to the post-processing block **30** used when the MRI data is from a gradient echo study. Figure 8A illustrates a correctly located final contour **CF** along the inner side of heart wall **H** bounding blood pool **B**. Figure 8B shows an incorrectly located final contour **CF** in which, because of relative thinness of heart wall **H**, final contour **CF** has lodged against the outer side of the heart wall. This may have occurred, for example, in a non-apical slice where a barrier **IB** is not used in the first active contour function ACF1 (seed-to-final propagation). The object of the post-processing is to identify such situations where final contour **CF** has lodged against a region of high gradient spaced from the contour feature to be extracted and to encourage the active contour away from such region. This may be accomplished by applying the barrier energy term **IB** and also by placing a plurality of volcanos **V** outside the heart wall **H**. Accordingly, referring also to Figure 8C, in block **68** (correction needed?) it is automatically determined whether such correction is necessary (i.e. whether there are any points on the contour proximate the barrier) and when so, the final contour **CF** is applied to a fifth active contour function **ACF5** followed by a sixth active contour function **ACF6**, such that there are first a maximum of 50 iterations (MI = 50) in the presence of image gradient and image barrier energy terms followed by a maximum of 100 iterations in the presence of image gradient IG and volcano **V** energy terms. A normal stiffness of the active contour (α = 1, β = 1) is used in each of the fifth and sixth active contour blocks **ACF5**, **ACF6**.

With the aforedescribed methods, final contours **CF** have been automatically extracted with the only user contour feature identifying input being that of the seed contour for the initial image $\mathbf{I}_{0,0}$. It should therefore be apparent that the objects of the present invention have been attained, and that numerous modifications, deletions to or additions in the details given of the preferred embodiments are possible within

the intended spirit and scope of the present invention.

Table 1, Legend to Figure 2

Block	
10	Input multislice multiphase MRI data
12	Set up propagation sequence
14	Barriers needed ?
16	Calculate barriers
18	Input seed contour in image at initial slice and phase
20	Propagate seed contour to final contour
22	Unprocessed adjoining slice to a processed image at initial phase ?
24	Propagate provisional contour **CF'** to seed contour for unprocessed adjoining slice
26	Unprocessed adjoining phase to a processed image ?
28	Propagate provisional contour **CF'** to seed contour for unprocessed adjoining phase
30	Post-process final contours
32	Applications (Volumes, Visualisation)

Table 2, Legend to figure 4

Block	
33	Images of all phases of predetermined slice
34	Average image over all phases
36	Mean (μ)
38	Standard deviation (σ)
40	μ - σ/4
42	Threshold at T
44	Canny function
45	Barrier for all phases of predetermined slice, **IB**

Table 3, Legend to figure 6C

Block	
47	Pair of profiles ($PR_{p,i}$:$PR_{c,i}$) normal to point i in **CF**
48	Vary displacement of centre point of $PR_{p,i}$ along $PR_{c,i}$
50	Correlation coefficient
52	Mean squared error
56	Displacement where match measure is maximum
57	Contour point i of **CN**

Claims

1. A method of extracting final contours fit to a contour feature in a collection of images of an object, each of said images representing a slice position, selected from a plurality of successively spatially displaced slice positions in the object, and a phase position, selected from a plurality of successive phase positions, said method comprising:

selecting an initial image from said collection of images, corresponding to a predetermined first slice position and a predetermined first phase position;

providing to said initial image a seed contour, proximate a contour feature in said initial image, to be extracted;

automatically propagating said seed contour with a seed-to-final propagation function to produce a final contour which is fit to said contour feature in said initial image;

said final contour being used as a provisional contour for an adjacent image, the adjacent image having the first slice position and a phase position either preceding or succeeding said first phase position or the adjacent image having the first phase position and a slice position either preceding or succeeding said first slice position;

automatically propagating said provisional contour for said adjacent image with a provisional-to-seed propagation function to a seed contour for said adjacent image;

automatically propagating said seed contours for said adjacent images to a final contour fit to said contour feature in said adjacent image.

2. A method according to claim 1, characterised in that a final contour fit to a contour feature in an earlier image is carried over to a further adjacent image as a provisional contour in the further adjacent image, said earlier image and said further adjacent image having identical slice positions or identical phase positions, the method further comprising:

automatically propagating said provisional contour for said further adjacent image with an provisional-to-seed propagation function to a seed contour for said further adjacent image; and

automatically propagating said seed contour for said further adjacent image to a final contour fit to said contour feature in said further adjacent image.

3. A method according to claim 1 or 2, characterised in that

a final contour fit of an earlier image having a slice position or final contour fits of a pair of earlier images having identical slice positions are carried over to a pair of further adjacent images having the same slice positions with said earlier image or said pair of earlier images and having phase positions which respectively immediately precede and immediately succeed the phase positions of said earlier image or said pair of earlier images, and

in that the provisional-to-seed propagation function is an in-slice provisional-to-seed propagation function; or in that

a final contour fit of an earlier image having a phase position or final contour fits of a pair of earlier images having identical phase positions are carried over to a pair of further adjacent images having the same phase positions with said earlier image or said pair of earlier images and having slice positions

which respectively immediately precede and immediately succeed the slice positions of said earlier image or said pair of earlier images, and

in that the provisional-to-seed propagation function is an in-phase provisional-to-seed propagation function.

4. The method as claimed in Claim 1,2 or 3, wherein said seed-to-final propagation function comprises applying a plurality of iterations of an energy minimizing active contour function having an energy which is a function of energy derived from the image at the active contour, active contour stretching energy and active contour bending energy.

5. The method as claimed in Claim 3, wherein said in-phase provisional-to-seed propagation function comprises forming rough contours by matching intensity profiles in an earlier image along normals to and proximate to said final contour in said earlier image to intensity profiles in said pair of further adjacent images along said normals and proximate to said rough contours in said pair of further adjacent images, and applying a spatial smoothing function to said rough contours.

6. The method as claimed in Claim 3 or 5, wherein said in-slice provisional-to-seed propagation function comprises thresholding said pair of further adjacent images to form for each an in-slice thresholded image, determining extended edges in the respective in-slice thresholded images, and applying said energy minimizing active contour function with an energy derived from said extended edges.

7. The method as claimed in Claim 5 or 6, wherein said spatial smoothing function comprises applying said active contour function to said rough contours in the absence of energy derived from the image but with a predetermined limited number of iterations.

8. A method of determining a relative volume of a blood pool in a heart chamber at a pair of generally opposed phase positions in a beating cycle from a collection of MRI images, each of said images representing a different combination of a slice position, selected from a plurality of successively spatially displaced slice positions in the heart chamber, and a phase position, selected from a plurality of successive phase positions in the beating cycle, said method comprising:

displaying on a display device an initial image from said collection of images, corresponding to a combination of a predetermined one of said phase positions and a slice position at a middle one of said slice positions;

receiving and displaying in said initial image a seed contour input by a user, via an input device, proximate an inner wall of said chamber defining said blood pool in said initial image;

using said seed contour as the only user input contour proximate the inner wall of said chamber, extracting a final contour defining said blood pool in each of said images; and

using said extracted final contour for each image in the first and second phase positions, computing said relative volume.

9. An MRI apparatus comprising means for generating and detecting magnetic resonance signals from a selected part of a body in different slices and at different phases of a movement occurring in said part of the body and means for forming a collection of images from said magnetic resonance signals, each image having a slice position and a phase position,

the MRI apparatus further comprising means for extracting, according to a method as claimed in any of the claims 1 to 7, final contours fit to a contour feature in said collection of images of the object said means comprising:

a display device for displaying an initial image from said collection of images corresponding to a predetermined first slice position and/or a predetermined first phase position;

means for providing to said initial image a seed contour, proximate a contour feature in said initial image, to be extracted;

means for automatically propagating said seed contour with a seed-to-final propagation function to produce a final contour which is fit to said contour feature in said initial image;

means for carrying over said final contour to an adjacent image, said final contour being used as a provisional contour for said adjacent image, the adjacent image having the first slice position and a phase position either preceding or succeeding said first phase position or the adjacent image having the first phase position and a slice position either preceding or succeeding said first slice position;

means for automatically propagating said provisional contour for said adjacent image with a

provisional-to-seed propagation function to a seed contour for said adjacent image;

means for automatically propagating said seed contours for said adjacent images to a final contour fit to said contour feature in said adjacent image.

10. An MRI apparatus as claimed in claim 9, the MRI apparatus further comprising means for computing a relative volume of a blood pool in a hart chamber from a collection of images at a pair of generally opposed phase positions in a beating cycle, wherein the contour feature to be determined by final contour fits is the inner wall of the heart chamber.

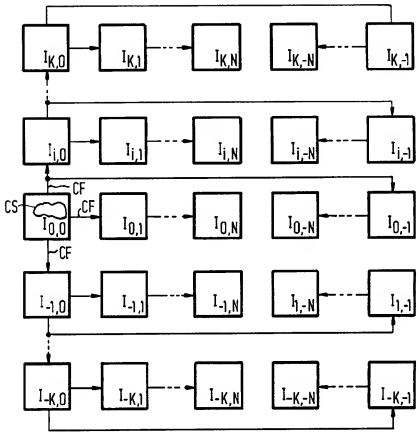

$I_{K,0}$
$I_{K,1}$
$I_{K,N}$
$I_{K,-N}$
$I_{K,-1}$
$I_{i,0}$
$I_{i,1}$
$I_{i,N}$
$I_{i,-N}$
$I_{i,-1}$
CF
CS
CF
$I_{0,0}$
$I_{0,1}$
$I_{0,N}$
$I_{0,-N}$
$I_{0,-1}$
CF
$I_{-1,0}$
$I_{-1,1}$
$I_{-1,N}$
$I_{1,-N}$
$I_{1,-1}$
$I_{-K,0}$
$I_{-K,1}$
$I_{-K,N}$
$I_{-K,-N}$
$I_{-K,-1}$

FIG. 1

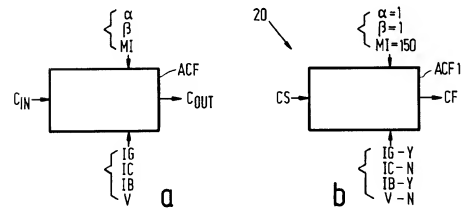

α
β
MI
ACF
C_{IN}
C_{OUT}
IG
IC
IB
V
a
20
α=1
β=1
MI=150
ACF1
CS
CF
IG-Y
IC-N
IB-Y
V-N
b

FIG. 3

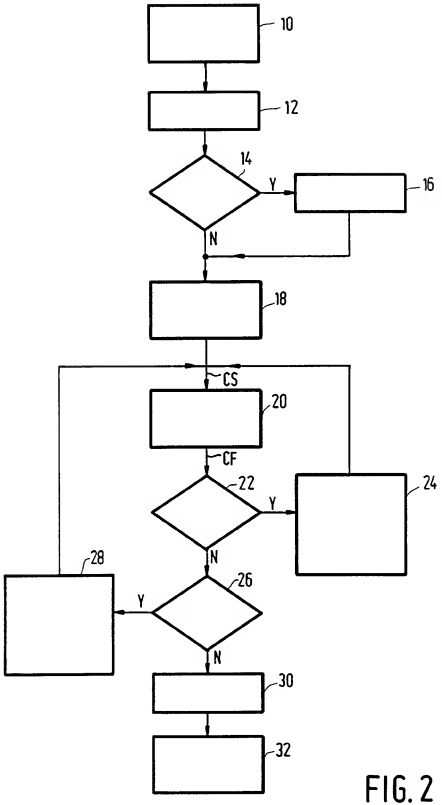


FIG. 2

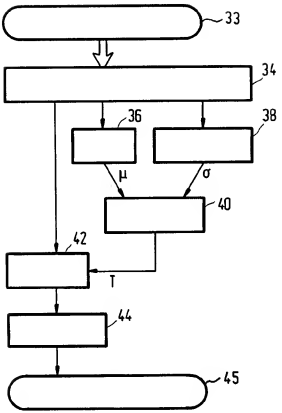

33
34
36
38
μ
σ
40
42
T
44
45

FIG.4

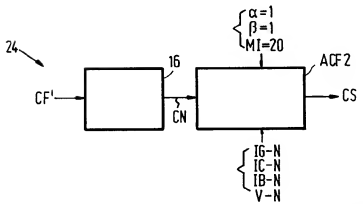
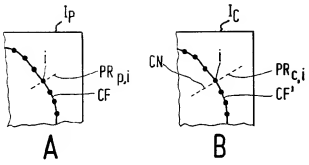

α=1
β=1
MI=20
24
16
ACF2
CF'
CS
CN
IG-N
IC-N
IB-N
V-N

FIG.5



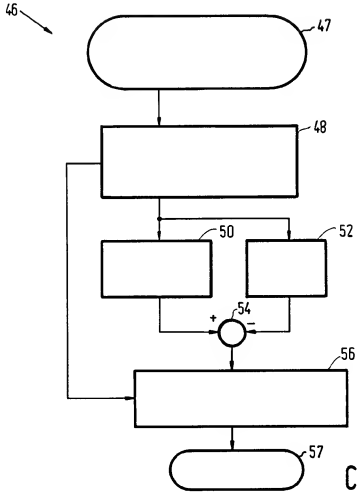


FIG.6

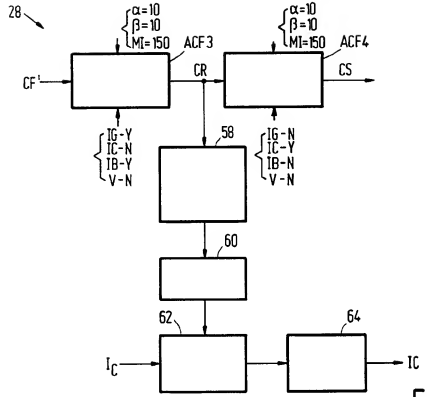

28
α=10
β=10
MI=150
ACF3
α=10
β=10
MI=150
ACF4
CF'
CR
CS
IG-Y
IC-N
IB-Y
V-N
58
IG-N
IC-Y
IB-N
V-N
60
62
64
I_C
IC

FIG.7

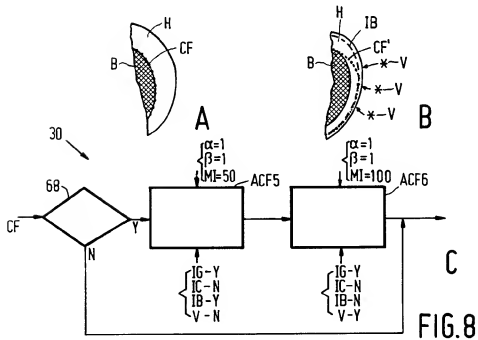

H
CF
B
A
H
IB
CF'
B
V
V
V
B
30
α=1
β=1
MI=50
ACF5
α=1
β=1
MI=100
ACF6
68
CF
Y
N
IG-Y
IC-N
IB-Y
V-N
IG-Y
IC-N
IB-N
V-Y
C

FIG.8

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EUROPEAN SEARCH REPORT

Application Number

EP 92 20 1893

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	FR-A-2 623 642 (THOMSON-RECHERCHE) * abstract * * page 1, line 1 - page 4, line 30 * ---	1	G01R33/56
A	DE-A-3 918 625 (HITACHI, LTD.) * abstract * * column 5, line 35 - line 50 * * column 6, line 20 - column 7, line 37; figures 1,2,4,5,7 * ---	1,8-10	
A,D	SECOND INTERNATIONAL CONFERENCE ON COMPUTER VISION 5 December 1988, TAMPA,FLORIDA, US pages 95 - 99 A.A. AMINI ET AL. 'USING DYNAMIC PROGRAMMING FOR MINIMIZING THE ENERGY OF ACTIVE CONTOURS IN THE PRESENCE OF HARD CONSTRAINTS' * the whole document * ---	1	
A	MAGNETIC RESONANCE IN MEDICINE. vol. 10, no. 1, 1 April 1989, DULUTH,MN US pages 145 - 155 S. MÜLLER 'SIMULTANEOUS MULTISLICE IMAGING (SIMUSIM) FOR IMPROVED CARDIAC IMAGING' * the whole document * ---	1,8-10	TECHNICAL FIELDS SEARCHED (Int. Cl.5) G01R G06F
A	PROCEEDINGS COMPUTERS IN CARDIOLOGY 19 September 1989, JERUSALEM, ISRAEL pages 211 - 214 S. EIHO ET AL. '3-D RECONSTRUCTION OF MYOCARDIUM FROM MRI AND A DISPLAY SYSTEM OF PULSATING 3-D HEART IMAGE' * the whole document * ---	1,8-10	
	-/--		

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	14 OCTOBER 1992	HORAK G.I.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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L : document cited for other reasons

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Page 2

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	MEDICAL PHYSICS. vol. 17, no. 2, 1 March 1990, NEW YORK US pages 258 - 263 D. KWIAT ET AL. 'A MAGNETIC RESONANCE IMAGING METHOD OF FLOW BY SUCCESSIVE EXCITATION OF A MOVING SLICE' * the whole document * ---	1,8-10	
A	EP-A-0 415 682 (GENERAL ELECTRIC COMPANY) * page 5, line 33 - page 7, line 46 * ---	1,8-10	
A	DE-A-3 835 111 (KABUSHIKI KAISHA TOSHIBA) * column 1, line 3 - column 2, line 4 * * column 3, line 1 - column 4, line 25; figures 1,2,5,6 * ---	1,8-10	
A,P	US-A-5 107 838 (K. YAMAGUCHI) * column 1, line 8 - column 2, line 25; figures 1,3,4,14 * ---	1,8-10	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)

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